

Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

SAFETY AND AVAILABILITY OF ROAD INFRASTRUCTURE DURING EXTREME NATURAL AND MAN-MADE EVENTS

**Jennifer Harder^a, Jörg Finger^b, Kalliopi Anastassiadou^{a*}, Kai Fischer^b, Alexander
Stolz^b**

^a *Federal Highway Research Institute, Brüderstraße 53, 51427 Bergisch Gladbach, Germany*

^b *Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, Am Klingenberg 1, 79588 Efringen-Kirchen, Germany*

Abstract

Extreme natural and man-made events can harm the road infrastructure facilities with substantial economic damages. The research presented in this paper focuses on the quantification of the availability and safety of road infrastructure during the occurrence of extreme events. It presents the first results of the implementation of Resilience Engineering to road infrastructure. This work is carried out within the framework of the BMVI Network of Experts of the German Federal Ministry of Transport and Digital Infrastructure as part of the research 'Quantification and prognosis of the availability and safety of road infrastructure in extreme events' which is a component of the topic 'Increasing the reliability of transport infrastructures' lead by the Federal Highway Research Institute (BAST).

Keywords: resilience; resilience engineering; extreme events; bridge; tunnel; transport infrastructure; road; network system; network analysis

* Corresponding author. Tel.: +49-2204-43-6302.
E-mail address: anastassiadou@bast.de

1. Introduction

An available and reliable road infrastructure is required in order to maintain individual traffic and transport of goods. Bridges and tunnels are important road infrastructure facilities due to their function as connecting elements and therefore represent critical assets. Extreme events, such as natural disasters or major accidents, can lead to damage or even structural failure of the road infrastructure facilities. The consequences can be enormous reconstruction costs and long out of service time, which cause substantial economic damages. The safety of infrastructure facilities must also be provided for all road users during the occurrence of extreme events, which are defined as events going beyond the regular design-relevant requirements of the existing code of practice. Such events, as heavy storms, had a significant negative impact on the safety and availability of road infrastructure in Germany during the spring of 2016. In North-Western Mecklenburg traffic obstruction caused by heavy rainfall and overturned trees were reported after the occurrence of heavy storms. At several locations the traffic on federal highways came partially to a standstill, see Eckermann (2016). In North Rhine-Westphalia road barriers and traffic disruption was reported due to a flooded tunnel and a landslide caused by heavy storms as reported by Treß (2016). Due to increased presence of heavy storms in 2016, the German Parliament concerned with this special issue. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) decided that these events are no longer isolated and considers them as a consequence of climate change, see German Parliament (2016). The events demonstrate that the safety and availability of the German transport infrastructure cannot always be ensured during the presence of extreme events. Restrictions of the road availability were noticeable in the affected areas for several days. The safety of road users can also be endangered by, for example, landslides or undercutting of bridge piers which reduce the loading capacity of bridges or if vehicles get stuck in flooded underpasses with their occupants.

The research presented in this paper focuses on the quantification and prognosis of the availability and safety of road infrastructure during extreme events. It presents the first results of the implementation of Resilience Engineering to road infrastructure in order to verify the adequacy of this approach for the evaluation and optimization of availability and safety. For this purpose, it is particularly important not only to identify vulnerabilities of the structures, but also to consider their regeneration times up to partial or complete recovery. Essential component of this assessment is the measurement of the resilience and the vulnerability at different levels (object and network level) in order to predict the infrastructure behavior during the presence of an extreme event. At object level the structural and operational condition of each individual infrastructure is investigated by a vulnerability analysis while at network level the function and relevance of the structure in the network is evaluated through a criticality analysis. In order to ensure the availability and safety existing measures, such as warning systems for wind on bridges or fire detectors in tunnels, are being considered and will be integrated into the developed methodology. The final objective is the development of a holistic resilience approach that quantifies and predicts the availability and safety of road infrastructure in extreme events in order to identify future hot spots in the road network with the need for further action. In order to achieve an improvement in resilience, a holistic assessment of the road infrastructure is necessary regarding the ability to minimize damage caused by extreme natural and man-made events and to get the road network back into operation quickly after the event.

2. The ‘Resilience Engineering’ approach

Extreme weather events, natural hazards and human or technical failures and deliberate acts can seriously damage road infrastructure facilities or affect its functioning. Nowadays, it is not possible to predict in detail whether and, if so, to what extent extreme events will occur and what impact they will have on the infrastructure. However, the risk-based approaches commonly used in practice today require assumptions, which are insufficient for such complex system observation. In this case, an approach is required, which is scenario-independent and takes into account the system resilience as well as its reactive probabilities.

In ‘Resilience Engineering’ several analysis and evaluation levels are used which interfere with each other. The smallest unit is used to determine indicators that reflect specific system specifications. These indicators serve to determine the system properties. Such system properties are for example redundancy and robustness or also safety and reliability. These system properties are again combined into capabilities of the overall system. Robustness and redundancy, for example, strengthen the capabilities of the system to ‘absorb’ the negative impacts of events on the function of the overall system. The individual capabilities are aimed at strengthening

the different dimensions of resilience. The difference between the dimensions could be a technical or organizational approach. An example of a hierarchical representation of infrastructure resilience indicators is given by Bologna et al. (2016).

The holistic concept of resilience engineering described above allows the quantification of resilience by finding suitable resilience indicators to address the system properties like safety, availability and reliability. In addition, this approach also allows a constant enhancement in order to quantify and evaluate additional capabilities and features classified as relevant in the future.

The key objective of the holistic resilience approach is to take into account all resilience phases from the failure to the re-commissioning of the road infrastructure. As a result, it is necessary to consider the road infrastructure on object level as well as part of the entire network (network level) and to establish a useful link between both. In addition, the potential impacts of extraordinary events on road infrastructure are first defined and analyzed. The focus of the impact analysis lays on the system properties that are affected by these events and is not scenario-based. Initially, specific events (the scenarios fire and flooding) are defined in order to analyze their impacts. The consideration of the impacts on the system properties leads to the fact that the safety and availability analysis is no longer necessarily based on specific events, but the approach is largely independent of the scenario. In this way, impacts of several extraordinary events can be investigated at the same time. The limitations of the system properties caused by man-made or extreme natural events can be quantified by using indicators for the measurement of the system properties in order to define the relevant input parameters (e.g. structural data, road traffic data). These indicators are also intended to enable a preselection or categorization of relevant structures by drawing up appropriate criteria. The defined indicators are used for the further development of existing processes in order to integrate them into the basic methodology of 'Resilience Engineering'. The final deliverable is a GIS-based software prototype, with which the developed methods and models can be demonstrated.

3. Quantification of road infrastructure safety and availability

3.1. Analysis on network level

To conduct an analysis of road transportation system on the network level it has to be represented as an abstract network or graph. According to Barabási and Pósfai (2016) the terms *network* and *graph* are used interchangeably in the scientific literature although there are subtle differences. Networks with *nodes* and *links* between them usually refer to real systems like a telephone, social or transportation network. On the other hand the term graph with its *vertices* and *edges* between them refers mostly to an abstract mathematical representation of the real network. In the following some basic concepts from graph theory relevant for our approach are explained.

A *graph* is an ordered pair $G = (V, E)$ comprising of a set V of n vertices (or nodes) and a set E of m edges (or links). Road networks are usually modeled by representing intersections as nodes and street segments between them as links. The *degree* of a vertex in a graph is the number of edges that are connected to it. In the case of an *undirected* graph the edges take the form of unordered pairs of vertices and are represented as lines between vertices in illustrations. In the case of a *directed* graph the edges take the form of ordered pairs of vertices and are represented as arrows in illustrations. In the context of road networks a one-way street is an example of a directed link. Furthermore in a *weighted* graph the edges have weights associated with them. In a road network these weights can for instance be geometric length or travel time associated with a link. In an *unweighted* graph the edges are not differentiated according to weights. The *shortest path* or *geodesic path* between two vertices is a path such that no shorter path exists, which means minimizing the sum of the weights of its constituent edges. To calculate the sum in the case of an unweighted graph all weights can be assumed to be equal to one. A *connected* graph is a graph in which any pair of vertices is connected by a path between them.

In their review of recent research on vulnerability and resilience of transport systems Mattsson and Jenelius (2015) distinguish between *topological* and *system-based* vulnerability analysis of transport networks. In both cases the transport network is represented as an abstract graph. In the system-based analysis the networks are usually weighted where geometric lengths or travel times in the real system are represented as weights of the edges in the abstract graph representation.

The presented research relies mostly on a topological analysis but also incorporate further system attributes like the distance between nodes / length of a link for the calculation of centrality measures.

In network analysis and the mathematical field of graph theory the aim of centrality measures is to find the most important vertices in a network. Initially applied for the analysis of social networks, centrality measures have been used to identify key infrastructure nodes in transportation networks. For a review of centrality measures in social and transportation networks the reader is referred to Mishra et al. (2012). Some of the main centrality measures are introduced below (for a detailed introduction see Newman (2015)):

Degree centrality is historically one of the first centrality measures and it is also one of the simplest. As stated above the degree of a vertex in a graph is the number of edges that are connected to it. Due to physical constraints there is only a limited range of possible values for the degree of nodes in road networks as opposed to other types of networks like for instance the internet that do not exhibit such constraints.

Closeness centrality is the average path length of the shortest path between a vertex and all the other vertices in the graph. In order to avoid infinite values for the distance d between vertex v and vertex w only connected graphs are considered. Closeness centrality is usually normalized by the number of vertices in the graph. Closeness centrality is applied to identify nodes that are “central” in a network. The closer a node is to all other nodes the more central it is.

Betweenness centrality for a vertex in a graph measures how often the vertex lies along the shortest path between two other vertices in the graph. In this way the vertex can be seen as acting as a “bridge” between the other two vertices. To calculate the betweenness centrality of a vertex v in a first step the shortest paths between two other vertices s and t are computed. Then the fraction of these shortest paths that pass through v is identified. This fraction is then summed up for all pairs of vertices (s, t) in the graph. Originally introduced by Freeman (1978) for the analysis of social networks betweenness centrality has since then also been applied for the analysis of transportation networks. For example Derrible (2012) compares the metro transportation network of several cities and emphasizes the importance of betweenness centrality for his analyses. Kermanshah et al. (2014) present an impact analysis of extreme events on road networks. In their research on the resilience of these networks they are using a network science and GIS approach. They simulate different kinds of extreme event scenarios for the road system of Chicago that differ in their special distribution like extreme flooding or a central targeted disruption. To measure the impacts of the scenarios they rely on betweenness centrality as a proxy for flows in the network and examine how the values for betweenness centrality are redistributed before and after a disruption. Their approach is similar to the work presented here and we will show an example of applying centrality measures – especially betweenness centrality – to the road network of North Rhine-Westphalia in section 4.

3.2. Analysis on object level

The road network is highly complex in nature and a resilience analysis requires a systematic approach. In alignment to Kröger and Zio (2011), a critical infrastructure can be hierarchically classified to evaluate single components and their contribution to the whole system. Fig. 1 shows this exemplary for the road network and the classification of bridges. Single sub-components can have links through physical and logical relations and this classification allows a systematic analysis of weak spots, which gives contributions to assess the resilience on object level.

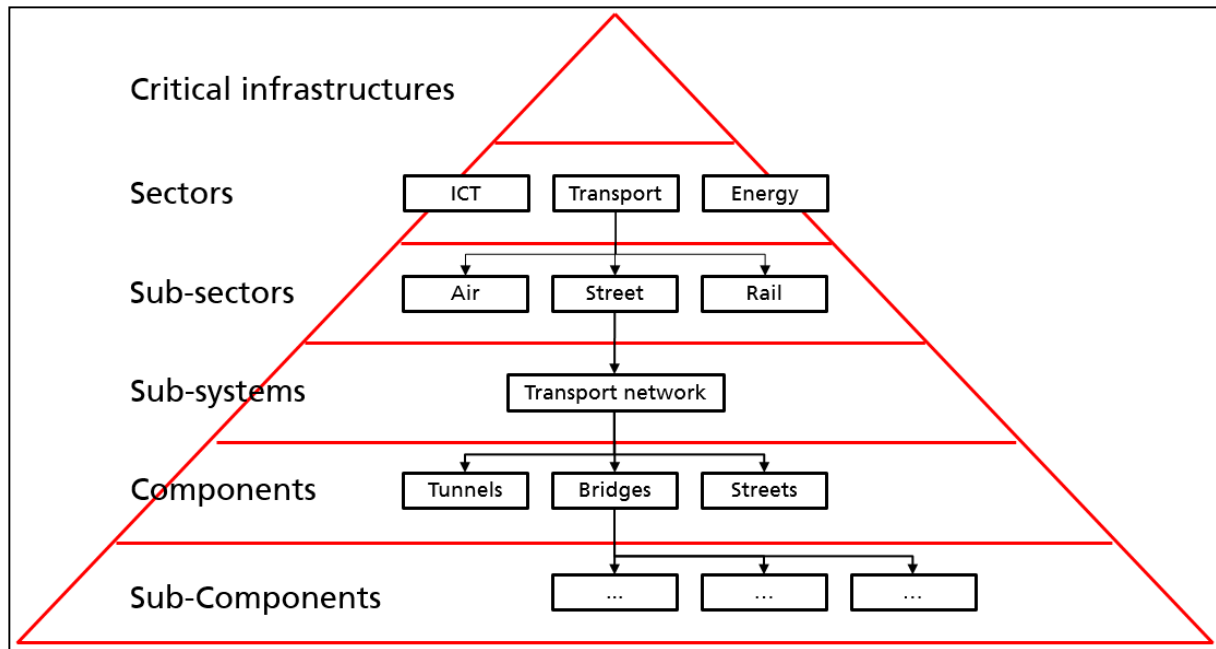


Fig. 1. Hierarchical classification of the transport network in alignment to Kröger and Zio (2011)

To characterize the resilience on object level, a new framework is developed and a generalized overview is shown in Fig. 2. Different resilience management phases can be directly addressed with this framework, as indicated in green. For a resilience cycle with the five resilience phases called prepare, prevent, protect, respond and recover see Thoma et al. (2016). The occurrence of a disruptive event (hazard) causes optional damage effects at the investigated object. The degree depends on the frequency, the intensity and the exposition to the hazard. Furthermore, constructional details determine the robustness or the degree of damage. The statistical occurrence quantifies constructional or dimensional properties of the object and the traffic load gives further contributions concerning the criticality. A small traffic load results in a small criticality, independent on the damage effects, for example.

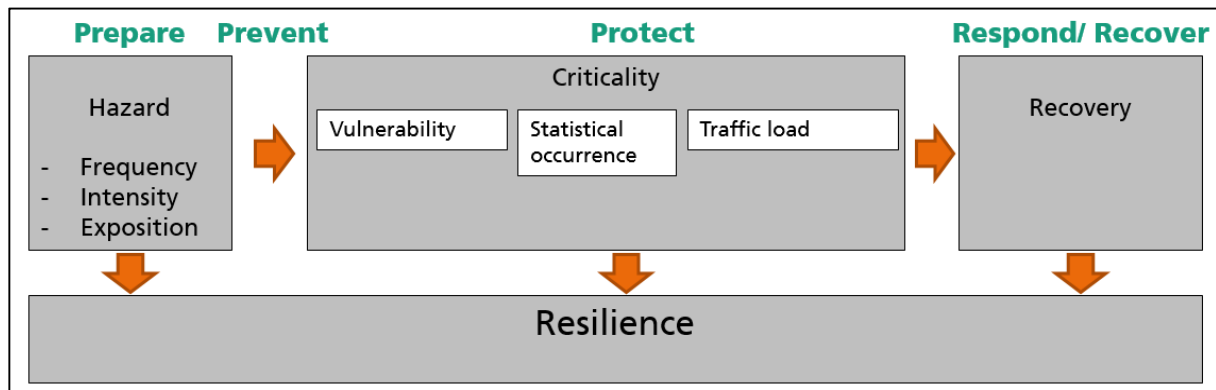


Fig. 2. Classification of the derived vulnerability quantities within the resilience framework for the evaluation of traffic network systems.

A comprehensive overview of the German road network and its engineered structures, like bridges and tunnels, is given in the database SIB and the corresponding instruction ASB-ING, see Bundesministerium für Verkehr, Bau- und Stadtentwicklung (2013). Currently, the database includes 39231 bridges on federal level and 26335 on federal state level. Each construction is categorized with certain attributes and builds the basis for a statistical evaluation of the resilience assessment on object level. For the current study, the statistical analysis includes the distribution depending on the system, construction type, length, span, age and the current state. This information is applied to derive weighting factors, which are included into the vulnerability analysis concerning the statistical occurrence. The left diagram in Fig. 3 shows exemplary the statistical occurrence of dimensional parameter of bridges in Germany. Based on this information, a construction for the assessment scheme in Fig. 2 is derived, as shown in the right pictures of Fig. 3.

Besides the statistical evaluation, the applied approach includes further a detailed analysis of single construction types, if single components will fail. With insights of the derived distributions, constructions with the highest occurrence concerning their material, system and length are characterized component-wise. Aim of the analysis is the identification of critical components and the comparison with the real state of a building.

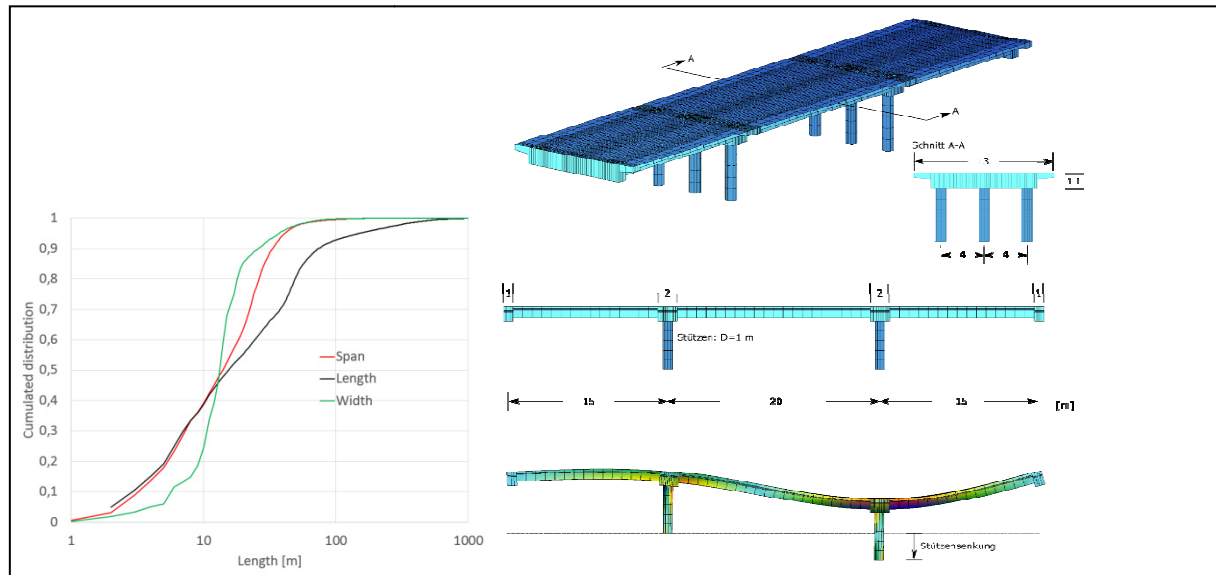


Fig. 3. Statistical occurrence of dimensional parameter of bridges in Germany (left) and the evaluation of a derived bridge construction based on the statistical occurrence (right) for an uneven reduction of a column as hazard scenario.

The results of the derived hazard-damage relation give contributions to characterize a performance target, e.g. the usability, over time and determine the degree for the required recovery. The time-dependent assessment of the expected loss builds the basis for resilience evaluation. The results of this approach can be applied to address the efficiency of different resilience enhancement measures, like prevention or protection.

3.3. Relation between network level and object level

In this section the relation between the network level and the object level is addressed. The analysis on the network level aims at identifying important and critical nodes and objects. For these critical elements an additional analysis on the object level is performed to assess the safety and availability of these elements. The investigations comprise of identification of resilience indicators that are suitable for ascertaining safety and availability. For these indicators methods for quantification will be developed. Through aggregation of the individual analyses on object level the safety and availability for parts of the network under investigation can be determined.

The object level analysis results in the characterization of a performance target over time. The evaluation of expected losses builds the basis to evaluate the resilience of a single construction. The loss of a single object decreases the usability rapidly and this information can be combined with the network level analysis where critical nodes are identified. Very critical nodes in combination with weak construction marks indicate possible weak spots.

4. Development of a GIS application

4.1. Input data

The road network data in the presented research consists of the federal highways ('Autobahnen', 'Bundesstraßen') in Germany. The dataset was exported from the federal information system for streets (Bundesinformationssystem Straße, BISStra) which is a geographic information system that consists of a core system and supplementary systems specialized in different domains Bundesanstalt für Straßenwesen (BASt)

(2015). See Fig. 4 for an illustration of the available road network data, where motorways ('Autobahnen') are represented with blue lines and rural federal roads ('Bundesstraßen') are represented with yellow lines. Additionally the thickness of the lines varies according to designations of the roads.

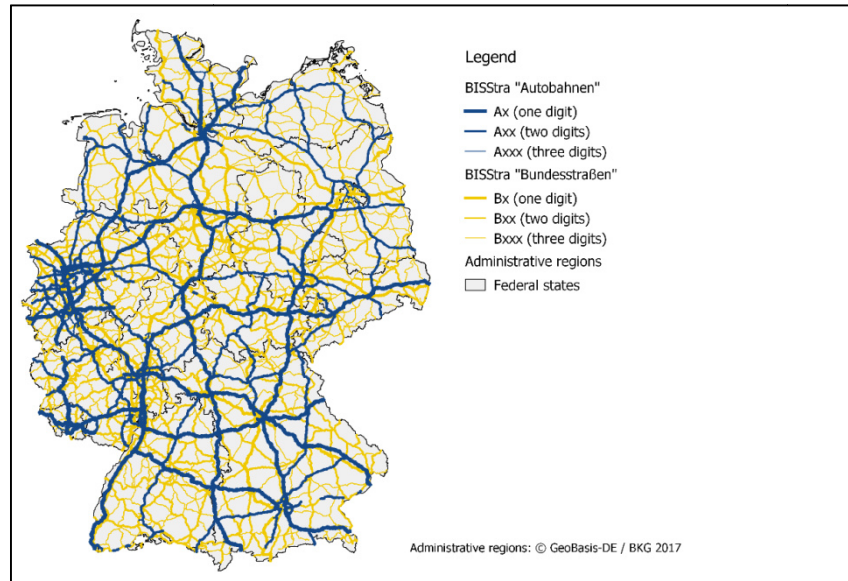


Fig. 4. Federal highways in Germany

4.2. Demonstrator

For demonstration and testing purposes the latest version of QGIS was used as a free and open-source desktop geographic information system QGIS developers (2017). The illustrations in this paper that show maps all result from this demonstrator.

For *network preparation* a plugin for QGIS was developed that uses functionality from the free and open source geographic information system GRASS (Geographic Resources Analysis Support System), see GRASS Development Team (2017), Neteler et al. (2012).

For the *network analysis* the functionality offered by GRASS GIS was extended by developing another plugin for QGIS that allows to access functionality offered by the free and open source Python library NetworkX, see NetworkX developers (2017).

4.3. Network analysis example

In this section the network preparation and network analysis are addressed. In order to perform a network analysis in a first step road data has to be converted into a network (graph) as an abstract representation. For the example presented here the network of primary federal motorways ('Autobahnen') in Germany was chosen. In the numbering system of the federal motorways the letter A stands for 'Autobahn' which is followed by a number. For the motorways of national importance that go across Germany only a single number is used.

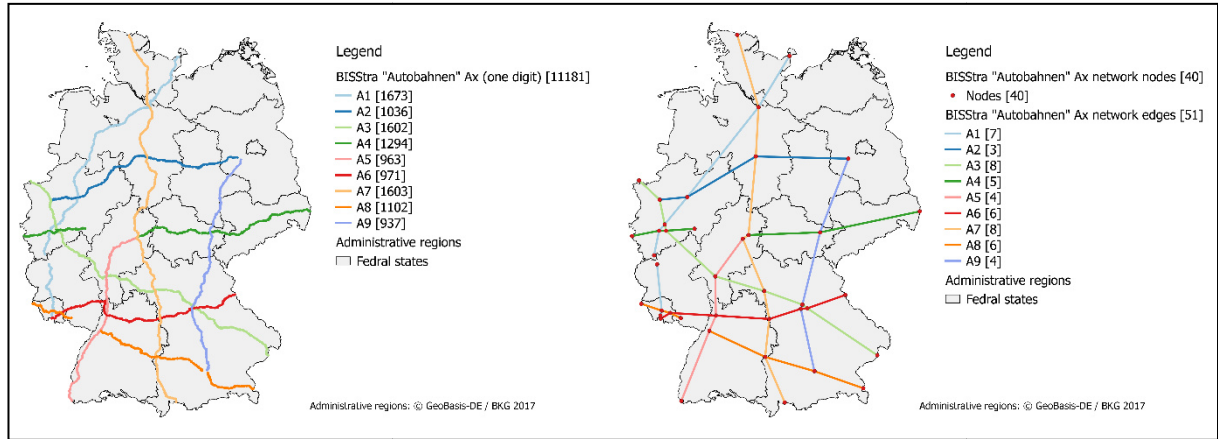


Fig. 5. (a) Major German Autobahn network; (b) abstract network representation

Fig. 5 depicts on the left side the example dataset of motorways A 1 through A 9 which consist of around 1000 to 1700 features per Autobahn. On the right side the corresponding abstract network representation consisting of 40 nodes and 51 edges is shown. The example dataset of primary motorways with national importance was chosen for the sake of a clear and comprehensible illustration. In our research we rely on more complex networks consisting of more extensive road network data.

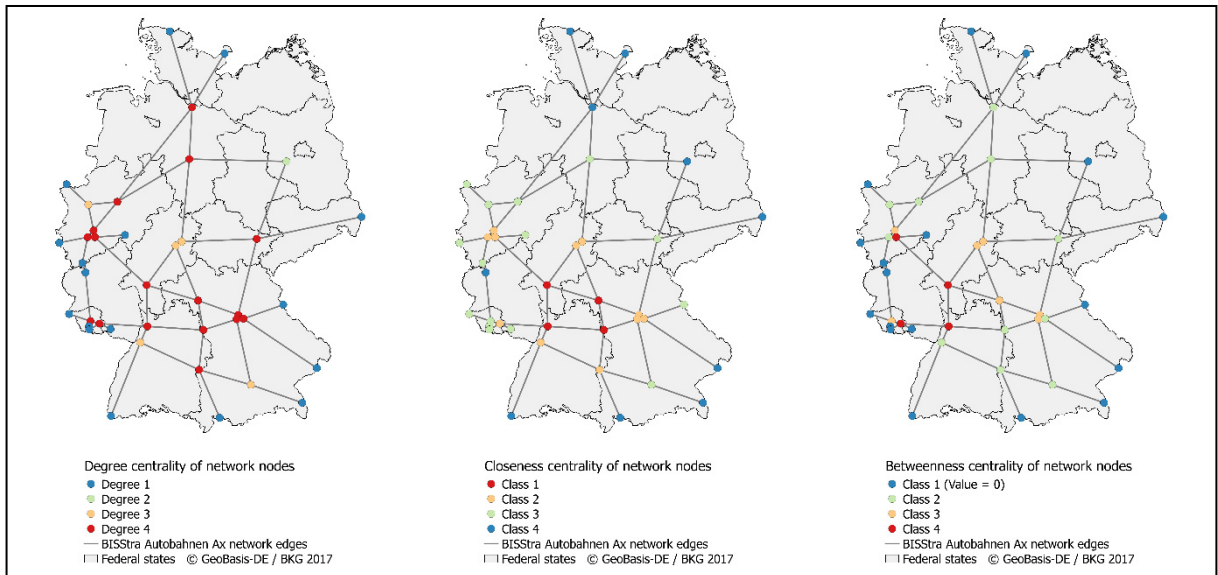


Fig. 6. Centrality measures: (a) degree centrality; (b) closeness centrality; (c) betweenness centrality

The illustration of a network analysis by means of centrality measures is based on the example described above. In Fig. 6 the three centrality measures introduced in section 3.1 are depicted, namely (a) degree centrality, (b) closeness centrality and (c) betweenness centrality (Neumann, 2015). Depending on the applied centrality measures different key infrastructure nodes are identified. The example contains nodes with four different degrees ranging from one to four. In the illustration these are depicted with four different colors (blue = 1, green = 2, yellow = 3 and red = 4), see Fig. 6 (a). This color scheme is also used for the other two illustrations Fig. 6 (b) and (c), by assigning the values of the centrality measures to four different classes, where blue stands for the lowest values and red for the highest values.

In the following we are focusing on betweenness centrality and how it changes as a disruption occurs. In a real world example we are examining a part of the road network of North Rhine-Westphalia in the area of Cologne and Düsseldorf. We investigate the impact of the closure of a certain bridge on the motorway A57 in the year 2012. Fig. 7 (a) shows the selected part of the road network around the affected bridge. Motorways ('Autobahnen') are depicted in blue and rural federal roads ('Bundesstraßen') are depicted in yellow. The abstract network representation is illustrated with white nodes and gray links. For a local analysis a part of the

network is selected by limiting the maximum distance from the considered bridge. Fig. 7 (b) shows the change in betweenness centrality after the removal of one link due to the closure of the bridge. The color gradient ranges from blue for an increase over white for no change to red for a decrease in betweenness centrality. Darker colors signify larger increases and decreases respectively. Using betweenness centrality as proxy for flow this gives an idea how the traffic is redistributed in the network.

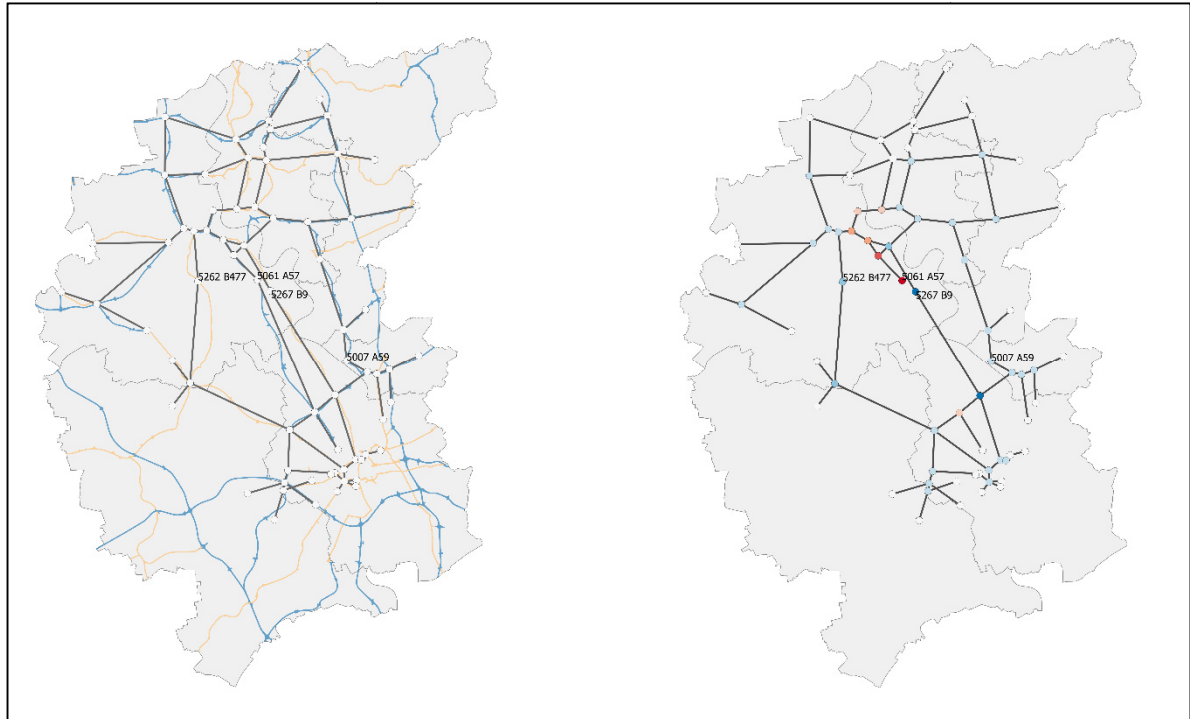


Fig. 7. (a) Road network and abstract representation; (b) Change in betweenness centrality due to removal of a link

For a validation of the results we compare the change in betweenness centrality resulting from removing one edge in the model with the change in recorded traffic data from the time periods before the disruption and after the disruption. To this end we examine data from permanent automatic counting stations on the affected road itself (A57) as well as on roads parallel to it (B477, B9, A59). We were already able to show that the predicted change by the model is in line with the observed actual change of the amount of traffic. We are now enhancing our model to incorporate additional information like the type of the road to get even more accurate predictions.

5. Output and further investigations

For a holistic assessment and forecasting of the availability of road infrastructure during the occasion of disruptive events, methods and concepts are needed that enable the management of the disruptions or damage in order to maintain or rapidly restore the functionality of an infrastructure.

In Germany, the presence of regression levels is of high relevance in order to maintain the function and operation of the road network during and after the presence of extraordinary events. This can be understood as both, the provision of redundancies at the infrastructure facility (object level) as well as the possibility of relocating traffic flows to evasion routes at the road network (network level). In addition, the aim is to examine the organizational and technical prerequisites for an immediate (re-)action of the responsible authorities, with the aim of ensuring the maintenance of the traffic route (or the damaged structure) in the case of an extraordinary event.

In addition, appropriate measures are to be identified those significantly reduce the loss of system functions and contribute to a faster re-commissioning of elements of the road infrastructure after the occasion of an extraordinary event. Through the use of these adaptation measures, both the initial state and higher system functionality can be achieved.

Within the framework of this project, methods and concepts shall be developed that allow the reaction and

restoration process to be designed and optimized more effectively than before, in order to minimize out of service time and financial costs that would result from failure and restoration after damage or destruction of the road infrastructure.

Acknowledgements

This work is carried out within the framework of the BMVI Network of Experts of the German Federal Ministry of Transport and Digital Infrastructure as part of the research ‘Quantification and prognosis of the availability and safety of road infrastructure in extreme events’ which is a component of the topic ‘Increasing the reliability of transport infrastructures’ lead by the Federal Highway Research Institute (BAST). Further information can be found at: www.bmvi-expertennetzwerk.de/EN. In addition, special thanks go to the bachelor student Can Altas at Fraunhofer EMI from the Baden-Wuerttemberg Cooperative State University (Duale Hochschule Baden-Württemberg / DHBW) for implementing QGIS plugins that realize network preparation and network analysis functionality.

6. References

- Barabási, A.-L., Pósfai, M., 2016. Network science. Cambridge, United Kingdom: Cambridge University Press.
- Bologna, S., Carducci, G., Bertocchi, G., Carrozzi, L., Cavallini, S., Lazari, A., Oliva, G., Trabalesi, A., 2016. Guidelines for Critical Infrastructures Resilience Evaluation.
- Bundesanstalt für Straßenwesen (BAST), 2015. Bundesinformationssystem Straße (BISStra). <http://www.bast.de/DE/Verkehrstechnik/Fachthemen/v2-bisstra.html>.
- Bundesministerium für Verkehr, Bau- und Stadtentwicklung, 2013. ASB-ING: Anweisung Straßeninformationsbank für Ingenieurbauten. Teilsystem Bauwerksdaten.
- Derrible, S., 2012. Network centrality of metro systems. *PloS one* 7, e40575.
- Eckermann, C., 2016. POL-HRO: Verkehrsbehinderungen nach Unwetter im Bereich Nordwestmecklenburg. <http://www.presseportal.de/blaulicht/pm/108746/3361244>.
- Freeman, L., 1978. Centrality in social networks conceptual clarification. *Social Networks* 1, 215–239.
- German Parliament, 2016. Bundestag zieht Bilanz der Unwetter-Zerstörungen. <https://www.bundestag.de/dokumente/textarchiv/2016/kw23-aktuelle-stunde-unwetter/426746>. Accessed 9/19/2017.
- GRASS Development Team, 2017. GRASS GIS: Official Website. <https://grass.osgeo.org/>. Accessed 8/18/2017.
- Kermanshah, A., Karduni, A., Peiravian, F., Derrible, S., 2014. Impact analysis of extreme events on flows in spatial networks, in *2014 IEEE International Conference on Big Data (Big Data)*. In: IEEE, pp. 29–34.
- Kröger, W., Zio, E., 2011. Vulnerable systems. London, New York: Springer.
- Mattsson, L.-G., Jenelius, E., 2015. Vulnerability and resilience of transport systems – A discussion of recent research. *Transportation Research Part A: Policy and Practice* 81, 16–34.
- Mishra, S., Welch, T., Jha, M., 2012. Performance indicators for public transit connectivity in multi-modal transportation networks. *Transportation Research Part A: Policy and Practice* 46, 1066–1085.
- Neteler, M., Bowman, M., Landa, M., Metz, M., 2012. GRASS GIS: A multi-purpose open source GIS. *Environmental Modelling & Software* 31, 124–130.
- NetworkX developers, 2017. NetworkX: Official Website. <http://networkx.github.io/>. Accessed 8/18/2017.
- Newman, M. E. J., 2015. Networks: An introduction. Oxford: Oxford University Press.
- QGIS developers, 2017. QGIS: Official website. <http://qgis.org/en/site/>. Accessed 8/18/2017.
- Thoma, K., Scharte, B., Hiller, D., Leismann, T., 2016. Resilience Engineering as Part of Security Research: Definitions, Concepts and Science Approaches. *European Journal for Security Research* 1, 3–19.
- Treß, K., 2016. Verkehrschaos als Folge des Unwetters. <http://www.wz.de/lokales/rhein-kreis-neuss/neuss/verkehrschaos-als-folge-des-unwetters-1.2203850>.